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Chronology of the halo globular cluster system formation

M. Salaris[1,2] **and A. Weiss**[1]

[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85740 Garching, Germany
[2] Institut d'Estudis Espacials de Catalunya, 08034 Barcelona, Spain

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Abstract. Using up-to-date stellar models and isochrones we determine the age of 25 galactic halo clusters. The clusters are distributed into four groups according to metallicity. We measure the absolute age of a reference cluster in each group, and then find the relative ages of the other clusters relative to this one. This combination yields the most reliable results. We find that the oldest cluster group on average is 11.8 ± 0.9 Gyr or 12.3 ± 0.3 Gyr old, depending on whether we include Arp2 and Rup106. The average age of all clusters is about 10.5 Gyr. Questions concerning a common age for all clusters and a relation between metallicity and age are addressed. The groups of lower metallicity appear to be coeval, but our results indicate that globally the sample has an age spread without a simple age-metallicity relation.

Key words: Galaxy: formation - Galaxy: halo - globular clusters: general — globular clusters: individual (M68, NGC6584, NGC3201, M5, M107, NGC6652) — stars: evolution

1. Introduction

The age of galactic Globular Clusters (GCs) provides fundamental information about the age of the universe and the formation history of the Galaxy. Recent improvements in the input physics needed for computing stellar evolutionary models have revived theoretical work on low-mass stars and GC age determinations (Chaboyer & Kim 1995, Mazzitelli et al. 1995, D'Antona et al. 1997, Salaris et al. 1997). Salaris et al. (1997 - Paper I) have shown that the age of the supposedly oldest clusters – the most metal-poor ones – is around 12 Gyr. This age reduction with respect to earlier work (e.g. Chaboyer et al. 1992, Salaris et al. 1993) has been identified to be mainly due to the use of an improved equation of state that includes non-ideal gas effects (Rogers et al. 1996).

Send offprint requests to: M. Salaris (e-mail address: maurizio@mpa-garching.mpg.de)

After this initial work, which was motivated by a possible "conflict over the age of the universe", the next step is to address the question of Galaxy formation. This means that one has to investigate many clusters and determine their ages, looking for correlations of age with cluster metallicity or galactocentric distance.

The position of the turn-off (TO) is the feature in the colour-magnitude-diagrams (CMD) of stellar clusters that is most sensitive to the age of the stellar population. The higher the cluster age, the less luminous and redder is the TO. Two differential quantities are suited as age indicators that are independent of reddening and distance: the brightness difference in V magnitude between the TO and the horizontal branch (HB) at the RR Lyrae stars region, called the $\Delta(V)$ or vertical method (see, e.g., Sandage & Cacciari 1990; Stetson et al. 1996 for a review) and the $(B-V)$ colour difference between the TO and the base of the Red Giant Branch (RGB), called the $\Delta(B-V)$ or horizontal method (see, e.g., Chieffi & Straniero 1989, VandenBerg et al. 1990). In both cases the TO position is differentially determined with respect to a CMD branch (the HB or the RGB) whose location is virtually independent of age in the case of old stellar populations.

Direct absolute age determinations based on the vertical method lead to a large spread in ages, which seems to be correlated with metallicity (Chaboyer et al. 1996). However, the quality and diverseness of the data do not favour this method. The horizontal method works best if all problems with theoretical effective temperatures (convection theory, atmospheres) and the conversion of theoretical quantities to observed colour and brightness are avoided. It therefore is very well suited for obtaining relative ages of clusters of similar metallicity, but absolute ages are very difficult to obtain.

A combination of both methods seems therefore to be promising for an accurate determination of absolute and relative ages. Clusters are inspected in groups of similar metallicity, and one or more suitable "template" clusters (with homogeneous and good photometry for both TO and HB region) are chosen to determine an absolute age directly with the vertical method. Then, the horizontal

method is used for a differential comparison with other clusters of the same group. This is the approach we have chosen (see also Paper I) and it is similar to the one by Richer et al. (1996). Our work differs from their analysis in that we use the vertical method for determining the absolute ages by virtue of theoretical isochrones and zero-age horizontal-branch models, while their absolute ages were obtained by fitting Bergbusch & VandenBerg (1992) isochrones, without explicitly using theoretical HB models; moreover we use new and improved stellar models (see Paper I), taking into account the latest developments regarding stellar opacities and equation of state.

The questions we want to address are: (i) what is the absolute age of one or more template cluster in each metallicity group; (ii) how do $\Delta(B-V)$ differences between clusters within a group translate into age differences? This information is necessary for the more global problem of whether there is an age spread between galactic clusters, and if so, whether it is correlated with metallicity. Assessing clearly the existence of an age spread among GCs and of an age-metallicity relation is fundamental for understanding the formation of our Galaxy. Very recently Chaboyer et al. (1996) found strong evidence in favour of a spread in the ages of galactic GCs and an age-metallicity relationship. On the contrary, Stetson et al. (1996) concluded that there is no evidence for a significant spread in ages among clusters of similar metallicity and that the case concerning age differences between metallicity groups remains unsettled, while Richer et al. (1996) found that the most metal-poor clusters may be slightly older than clusters of higher metallicities. The results of the latter group are, however, neither inconsistent with a picture in which all clusters of all metallicities formed simultaneously. Between the most metal-rich clusters there appears to be a considerable age spread of ~ 2 Gyr (VandenBerg et al. 1990), and in addition a number of exceptional clusters were found in all investigations.

In the present paper we restrict ourselves to halo clusters - that means GCs with kinematic properties typical of the halo component of the Galaxy - and try to answer both the questions concerning the distribution of ages within individual metallicity groups and between groups. In Sect. 2 we will review our method used for determining absolute and relative cluster ages. Sect. 3 contains our results for a large group of halo clusters, which are compared with the results by Richer et al. (1996). In Sect. 4 the implications for the cluster age distribution are discussed, and a summary of our results follows in the final section.

2. Method

2.1. Stellar Models

As in Paper I we rely on theoretical models for all evolutionary phases; in particular we have computed stellar models from the main-sequence (MS) up to the zero-age horizontal branch (ZAHB). The input physics employed in the models is the same as in Paper I: for the opacities we used a combination of the latest OPAL opacities (Rogers & Iglesias 1992; Iglesias & Rogers 1996) and tables from D. Alexander (Alexander & Ferguson 1994; Alexander, private communication). The metal mixtures included identical α-element enhancement for all opacity tables. The equation of state consisted of the OPAL EOS (Rogers, Swenson & Iglesias 1996) with extensions for the lowest temperatures and degenerate helium cores taken respectively from Chieffi & Straniero (1989) and Straniero (1988).

Diffusion of helium and heavy elements is not included in the calculations. The effect of diffusion on the ages obtained from our models is discussed in Sect. 2.4, which is dedicated to the methods for determing absolute and relative ages.

We computed stellar models for the following compositions: $(Z,Y) = (0.0002, 0.230)$, $(0.0004, 0.230)$, $(0.0006, 0.232)$ $(0.0008, 0.232)$, $(0.001, 0.233)$, $(0.0015, 0.235)$ $(0.002, 0.236)$, $(0.004, 0.242)$. For $\triangle Y/\triangle Z$ we have taken a mean value of 3 (as in Bergbusch & VandenBerg 1992; Mazzitelli et al. 1995). The first two mixtures are those already used in Paper I. α-elements are always enhanced (e.g. [O/Fe] = +0.5); the total metal-abundance [M/H] is about 0.2-0.3 dex higher than [Fe/H].

Stellar models with masses between 0.7 and $1.0 M_{\odot}$ were evolved from the zero-age main sequence up to the RGB. The mixing length has been calibrated as explained in Paper I. Isochrones for different ages were computed from these evolutionary models. ZAHB models with varying envelope masses were calculated as described in Paper I.

Similarily, the conversion from theoretical effective temperature and luminosity to observable colour $(B-V)$ and visual magnitude V was done using the transformations of Buser & Kurucz (1978, 1992).

2.2. Globular Clusters groups

In this paper (as in Paper I) we have used both the vertical and the horizontal method for determining the distribution of the halo GCs ages. The strengths and weaknesses of these techniques have been discussed extensively in many recent papers (VandenBerg et al. 1990, Salaris et al. 1993, Chaboyer et al. 1996). To summarize, the $\Delta(V)$ appears particularly suitable for the determination of the absolute clusters ages, since it is independent of the treatment of convection and is only weakly sensitive to metallicity. However, it can be safely applied only in the case of clusters with homogeneous photometry for both TO and HB, and with a well populated horizontal part of the HB. Clusters with only a blue, vertical HB are in principle excluded, because it is impossible to have observational estimates of the absolute HB luminosity in the RR Lyrae region or to constrain the age from the fit of theoretical ZAHB models.

The $\Delta(B-V)$ can in principle be applied to each kind of GC with sufficiently accurate photometry, since each GC shows a main-sequence TO and an RGB. It is only weakly sensitive to metallicity, but absolute ages depend on the mixing length calibration and on the transformations from effective temperatures to colours. When all the problems related to the $T_{\rm eff}$ determination and the conversion to observed colours are minimized, as in the case of clusters with similar metallicities, the horizontal method turns out to be suitable for accurately determining the relative ages of clusters (VandenBerg et al. 1990, Stetson et al. 1996).

Since our goal is to study the distribution of ages of a well populated sample of halo GCs, one has to deal with clusters with very different HB types and with photometries not always extended up to the HB, or showing only a scarcely populated or blue HB. Therefore, we have to apply a combination of both methods for getting the ages of the cluster sample.

We have collected published CCD data for 25 halo clusters (see Table 1), which span a wide range of metallicities, galactocentric distances and HB types, divided into four groups according to their metallicity. The first group spans the range $-2.1 \leq$ [M/H] < -1.6 (metal poor clusters), the second $-1.6 \leq$ [M/H] < -1.3 (intermediate metal poor clusters), the third $-1.3 \leq$ [M/H] < -0.9 (intermediate metal rich clusters) and the fourth $-0.9 \leq$ [M/H] < -0.6 (metal rich clusters). The adopted [Fe/H] values come from Zinn (1985), and the global metallicity has been obtained considering an average $[\alpha/\mathrm{Fe}] = 0.3$ and [M/H] = [Fe/H] + 0.2 according to the discussion in Paper I. The metallicity difference among the clusters in each group is about a factor of 2. In the case of Rup106, Arp2 and Ter7, for which there are no data in Zinn (1985), we have considered the [Fe/H] estimates by Buonanno et al (1993, 1995a, 1995b) to which we have added the contribution of the α-elements [1], assuming that such an enrichment exists for these clusters as well.

We have considered only clusters with photometries that show at least MS, TO and RGB, and that permit a clear determination of the TO position (within an error $\leq \pm 0.15$ mag). In each group one cluster (or two clusters, if possible) is selected as the "reference" one, and its absolute age is determined directly by means of the vertical method; the photometry of the reference cluster has to show not only a clearly defined TO position, but also the RGB and a well-populated HB of such morphology that the ZAHB level can be safely determined. Thus, CMD morphology is more important than the overall quality of the photometry for a cluster to be suitable as a reference cluster.

Within each group the relative ages with respect to the reference cluster are determined by means of the horizontal method. Where there are two reference clusters the age difference from the vertical method can be cross-checked with that derived by means of the horizontal one.

2.3. Absolute age determination

The advantage of using the vertical method for determining the absolute age of a cluster is that it is largely independent of all uncertainties connected with the calculation of effective temperatures and their conversion to colours. It does not depend on the reddening and on the assumed distance modulus (the same holds, of course, also for the horizontal method), although the models yield a distance scale (by means of the comparison between observed and theoretical ZAHB level), which can be compared to independently determined values.

To obtain the cluster age, the procedure is the following: from the observed brightness of HB stars the apparent ZAHB brightness is derived (see below); with the TO-brightness as given by the observers, ΔV is determined uniquely and is compared to theoretical predictions of ΔV as a function of age for isochrones and ZAHB models of the appropriate metallicity. These steps are sufficient to find the cluster age.

However, one can go beyond this to check the reliability of the results. First, the difference between observed apparent and theoretical absolute ZAHB brightness gives the distance modulus following from our models, which can be compared to independent determinations from other distance indicators; thus, the distance modulus provides an independent way to assess the reliability of the derived ages.

Second, the isochrone can be compared to the CMD. Since age and $(m-M)_V$ already have been fixed, isochrones (and ZAHB models) remain to be shifted in colour to match the observed MS. This shift corresponds to the cluster reddening $E(B-V)$. The overall fit to the observed CMD may serve as an additional qualitative indicator. There is, however, the following point to be taken into account: since our age determination method does not rest on detailed isochrone fitting, we have taken the metallicity directly from the literature, without trying to improve the fit by exploring the error range in [M/H]. Changing the metallicity within the allowed range can improve the isochrone fit (see Sect. 3.2) without affecting appreciably the determined age.

[1] Carretta & Gratton (1997) recently have recalibrated the Zinn & West (1984) [Fe/H] scale, which corresponds to the Zinn (1985) metallicity scale for almost all GCs in our sample. The new calibration is based on a homogeneous set of cluster [Fe/H] determinations from high resolution spectroscopic data; it provides [Fe/H] values for the clusters in our sample that are on average 0.20 dex higher than the ones we used. This simply corresponds to an almost constant shift of the [M/H] ranges adopted for our GCs groups, but the membership of each single group does not change and similarly the absolute and relative ages we derive are only very marginally affected by the choice of this new scale (see Sect. 3, which is about age determination).

An important step in the vertical method is therefore to fix the zero-age level of the observed HB. In Paper I we selected two clusters (M68 and M15) with well-populated HBs and a sufficiently large number of RR Lyrae variables. With the mean brightness ($\langle V_{\rm RR}\rangle$) of the variables fixed, we derived the zero-age level using the relation by Carney et al. (1992):

$$V_{\rm ZAHB} = \langle V_{\rm RR}\rangle + 0.05[{\rm Fe/H}] + 0.20 \tag{1}$$

We have also demonstrated in Paper I that (assuming a constant helium content of $Y = 0.23$) our theoretical relation between ZAHB brightness (taken at $\log T_{\rm eff} = 3.85$) and [Fe/H] together with Eq. 1 agrees nicely with that found empirically by Clementini et al. (1995) and also supports that of Walker (1992a). The reader is referred to Paper I for a deeper discussion about the problem of the 'true' observational relation between RR Lyrae luminosities and metallicity. In the present paper we consider an initial helium abundance varying with Z, but the difference with the ZAHB luminosities obtained in Paper I is always less than 0.04 mag (reached at the highest metallicities considered). In Fig. 1 we show the final relation between ZAHB luminosity and [Fe/H] from our stellar models; in the same figure the empirical relations by Clementini et al. (1995 - when considering only ZAHB objects) and Walker (1992a) are also displayed (upper and lower limits according to the errors given by the authors). The agreement between the ZAHB theoretical models and both empirical determinations is evident.

Very recently, first results on the absolute luminosity of HB (Feast & Catchpole 1997; de Boer et al. 1997) and subdwarfs stars (Reid 1997; Gratton et al. 1997) based on HIPPARCOS data have appeared. The implications of the latter papers for the distances to M68 and M5 we will discuss in the respective sections. Feast & Catchpole (1997) used the trigonometric parallaxes of galactic Cepheid variables for recalibrating the zero-point of the period-luminosity relation. After applying a correction for metallicity effects, they derive a distance modulus of 18.70$\pm$0.10 for the LMC, almost 0.20 mag higher than the value commonly used, based on a previous Cepheids calibration and on other distance indicators (see, e.g. Walker 1992a). This distance modulus, coupled with the RR Lyrae observations by Walker (1992a) for LMC clusters, provides a mean absolute magnitude $\langle V_{\rm RR}\rangle = 0.25 \pm 0.10$ at [Fe/H]=-1.9 for RR Lyrae stars; this value corresponds, by applying Eq. 1, to $V_{\rm ZAHB} = 0.36 \pm 0.10$. From our theoretical models we get an absolute ZAHB luminosity $V_{\rm ZAHB} = 0.51$ at the instability strip for the same metallicity. This means that our theoretical value would be higher than the upper limit of the observationally allowed range (0.46) by 0.05 mag.

The opposite conclusion can be reached when considering the results by de Boer et al. (1997), again based on HIPPARCOS parallaxes; they present absolute V magnitudes for a group of HB field halo stars, bluer than the instability strip. We consider for example the reddest star in their sample (HD161817), which is also the object with the smallest error on M_V (the errors for the other stars are much bigger, up to 1.25 mag). The observations give $M_V = 0.72 \pm 0.25$ and $(B-V)_0$=0.14. The metallicity of the objects is not given in the paper. By using our theoretical ZAHB models with $[{\rm Fe/H}] = -1.03$ (as done by the authors when comparing their data with the ZAHB models by Dorman 1992) we obtain $M_V = 0.67$ at $(B-V)_0$=0.14. If we consider the models with $[{\rm Fe/H}] = -1.6$, which corresponds approximately to the average metallicity of field halo stars, we obtain $M_V = 0.58$. Both values are in agreement with the observationally allowed range. If, however, we take into account the fact that HD161817 is likely to be evolved from the ZAHB towards higher luminosities (as also noted by de Boer et al. 1997), then the theoretical models are more luminous than observationally allowed. Therefore, the two papers discussed lead to discrepant results. Compared to Feast & Catchpole (1997) our predicted distance moduli appear to be too low; compared to de Boer et al. (1997) they are too large. The first results based on HIPPARCOS data do not disprove the reliability of our theoretical ZAHB luminosities.

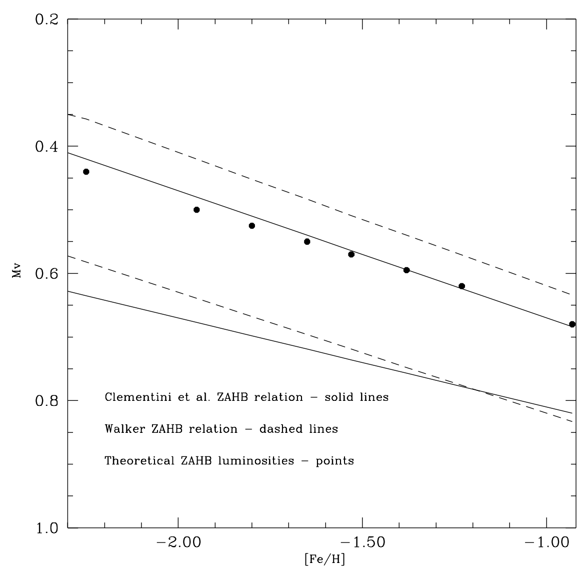

Fig. 1. Theoretical ZAHB luminosities as a function of [Fe/H]. Solid and dashed lines represent the upper and lower envelopes of the empirical determinations by Clementini et al. (1995) and Walker (1992a)

To determine the observational ZAHB brightness, the application of Eq. 1 requires good HB photometry and the

presence of a sufficient number of RR Lyr stars. It was not possible for all metallicity groups to find a cluster fulfilling both requirements. Therefore, we developed a method to determine the observational ZAHB level when the HB is well populated. This can be applied each time the observational HB is populated in the horizontal part, even if there are no stars in the instability strip.

Theoretically, all observed HB stars should be at least as bright as the ZAHB. Thus, the lower envelope (for well-populated HBs) to the observed HB provides a reasonable estimate for the ZAHB luminosity (Sandage 1990). In practice, however, photometric errors, field stars and other objects not belonging to the HB will spread out this lower limit and a more statistical approach is necessary. To this end we have looked into the brightness-distribution of HB stars in a few colour bins. For each colour bin count histograms for brightness bins were created; the brightness bins were typically 0.04-0.05 mag wide (depending on the HB population). Formally, we set the ZAHB level to the upper brightness of that bin which shows a decrease in star counts by a factor ≥ 2 and where the brighter bins contain more than 90% of all candidate HB stars under consideration. This is illustrated in Fig. 2 for M5. For all the clusters to which we have applied the vertical method these two conditions were always fulfilled by the same luminosity bin. For M68 and M15, our method reproduces the ZAHB levels at the RR Lyrae instability strip as determined by Eq. 1 (Paper I) within 0.01 mag, i.e. within the binning error. In this paper we will adopt for M68 the ZAHB luminosity and the associated formal error (the width of the luminosity bin) determined with the new method; the resulting absolute age is the same as in Paper I, but the formal error is lower (see Table 1). Note that the way we define the ZAHB level leads to a systematic overestimate of the ZAHB brightness of order half the bin width and consequently to ages slightly too high; the uncertainty, however, remains below $\approx$ 0.04-0.05 mag.

To check the influence of the chemical composition on our vertical-method age estimates, we have shown in Paper I (but see also Salaris et al. 1994; Chaboyer 1995) that a variation of the metallicity by a factor of 2 or the use of an initial helium abundance Y different by 0.01 in the theoretical isochrones changes the derived ages by slightly less than 1 Gyr. When taking into account also helium and heavy element diffusion, contrary to our expectations expressed in Paper I, the vertical-method ages derived decrease by less than 1 Gyr because of balancing effects on TO and ZAHB (Castellani et al. 1996).

2.4. Relative age determination

In deriving the relative GC ages we have applied the horizontal method, following the procedure presented by VandenBerg et al. (1990). The ridge lines of two clusters are shifted horizontally in order to match their TO colours,

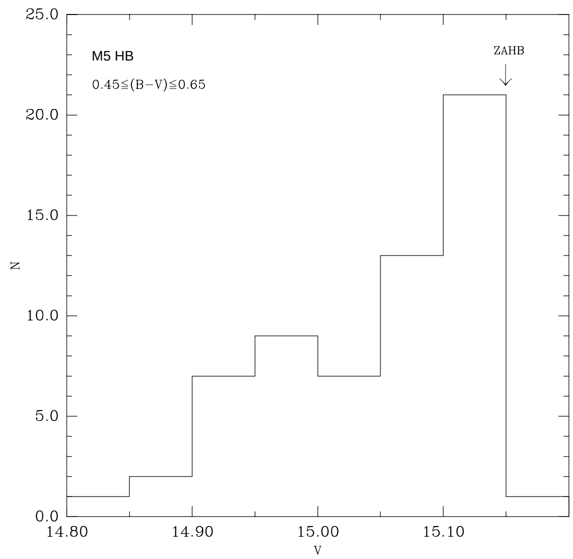

Fig. 2. Brightness distribution of M5 HB stars in the colour region $0.45 < (B-V) < 0.65$. The arrow marks the ZAHB level determined by both the total number of stars above this bin and by the decrease in the number of stars per bin

and then vertically to force coincidence between the main sequences at a position 0.05 mag redder than the TO. Differences in the RGB colour (fixed for example at a point 2.5 mag more luminous than the MS reference point) correspond to age differences derived from our new theoretical isochrones. As already discussed by VandenBerg et al. (1990), the precise point on the RGB is of little significance, since the RGBs run essentially parallel to one another. We have evaluated *mean* $\Delta(B-V)$ differences from the cluster fiducials by considering, when possible, a magnitude range along the RGB of typically 0.5-1.0 mag (depending on the extension of the fiducial line), starting approximately from the point 2.5 mag more luminous than the MS reference point. The formal error of the relative ages derived by means of this procedure, estimated from the uncertainty in measuring the shift in the position of the RGB with respect to the reference cluster is about 0.5 Gyr.

As for the reliability of the age scaling derived adopting the $\Delta(B-V)$ technique, the following points have to be mentioned:

i) A comparison of the $\Delta(B-V)$ scaling with respect to the age at fixed global metallicity, by adopting the oxygen-enhanced Bergbusch & VandenBerg (1992), the scaled-solar Straniero & Chieffi (1991) and our own isochrones shows a good agreement in spite of different codes, different effective temperature normalization and/or completely different input physics and heavy element distri-

bution. The relative ages obtained in the three cases differ by no more than 20%.
ii) The effect of a variation in the initial helium content is almost negligible. A variation of $\delta Y = \pm 0.01$ induces a change in the relative ages of only ≈ 0.15 Gyr.
iii) A variation in the global metallicity by a factor of 2 changes the relative ages by less than 0.5 Gyr.
iv) A global change of the mixing length parameter $\alpha_{\rm MLT}$ for each metallicity affects *absolute* ages derived by means of the horizontal method much more than the *relative* ones. A variation of $\alpha_{\rm MLT}$ by ± 0.1 changes the relative ages by 0.10-0.15 Gyr only, while changing the absolute ages by ≈ 1 Gyr.
v) The influence of the helium and heavy element diffusion on the relative ages obtained by means of the horizontal method is almost negligible (Cassisi 1996, private communication). A check at $Z = 0.0002$ shows that the age differences determined with and without including diffusion agree within 10%.
vi) The scaling of $\Delta(B-V)$ with respect to the age is independent of the absolute age only for ages higher than a certain value (depending on the metallicity). Below this limit, which, for example, is around 11-12 Gyr at $Z = 0.0002$, the age differences depend on the absolute ages assumed for the reference clusters; it is therefore important to fix the absolute age of the reference cluster within each group by means of the vertical method.

3. Cluster ages – absolute and relative

In this section we will discuss separately the absolute and relative age determinations of the clusters within each of the four metallicity groups. All the selected clusters, their metallicity, HB type, galactocentric distance (R_{GC}), the derived ZAHB luminosity (and the associated error) for the reference clusters, relative and absolute ages (with their formal errors), are displayed in Table 1. The ZAHB luminosities refer to the instability strip for M68 and to the red boundary of the instability strip for NGC6584, NGC3201 and M5, which have a well developed HB but no homogeneus RR Lyrae photometry. In the case of NGC6171 and NGC6652 the ZAHB luminosity corresponds to the red HB. The HB types come from Chaboyer et al. (1996). An evaluation of the galactocentric distances (in Kpc) has been obtained by applying the following equation:

$$R_{GC} = ((R_{GC}^{\odot})^2 + d^2 - 2dR_{GC}^{\odot}cos(l)cos(b))^{0.5} \qquad (2)$$

where b and l are the cluster galactic coordinates, $log(d) = (((m-M)_o + 5)/5) - 3$ (using A_V=3.3E(B-V)), and the Sun's galactocentric distance is set to $R_{GC}^{\odot}$=8.0 Kpc. The apparent distance moduli were obtained using our theoretical ZAHB models and the ZAHB luminosities given in Table 1 for the reference clusters, or the average HB magnitudes given by Chaboyer et al. (1996; in the case of NGC6366 the average HB luminosity comes from Alonso et al. 1997), translated into ZAHB luminosities by means of Eq. 1. The reddening values come from our work (and paper I in the case of M68) for the "reference" clusters, from Alonso et al. (1997) for NGC6366, and from Chaboyer et al. (1996) for all others.

A simple estimate of the formal error in the absolute age for the reference clusters is obtained as in Paper I, by statistically adding the formal uncertainties on the ZAHB level (displayed in Table 1) and on the TO luminosity (as derived from the original papers) in order to obtain the error in the observed $\Delta(V)$ value; this error is then transformed into an uncertainty in the age by using the theoretical isochrones. For the other clusters the formal error in the relative ages derived by means of the horizontal method (see the previous section) is statistically added to the error in the age of the corresponding reference cluster.

At this point we have to comment on the meaning of the formal errors given in Table 1. These errors have no true statistical meaning and therefore the results of the statistical analyses of Sect. 4 should be considered as being indicative and not rigorous. Chaboyer et al. (1996), who commented on this, have argued that the errors quoted by the observers correspond to 1.63σ, and since these errors referring to the HB or TO brightness are of a similar kind as those given in Table 1, our errors could be considered as corresponding to 1.63σ. However, we prefer to be more conservative and assume that they are of the order of 1σ. An argument in favour of this is that according to Chaboyer et al. (1996) the average 1σ error for all their clusters is 0.083 mag – corresponding to ≈1 Gyr, which is a similar age uncertainty as we give in Table 1.

3.1. Metal-poor clusters: $-2.0 \leq$ [M/H] < -1.6

The clusters belonging to this group are M68 (Walker 1994), M15 (Durrell & Harris 1993), M92 (Stetson & Harris 1988), M30 (Richer et al. 1988), NGC6397 (Buonanno et al. 1989), NGC2298 (Janes & Heasley 1988), Rup106 (Buonanno et al. 1993) and Arp2 (Buonanno et al. 1995a).

The reference cluster is M68, and its age determined as in Paper I by means of the vertical method is 12.2±1.0 Gyr. The distance modulus we derive from our ZAHB models is 15.26 ± 0.06. The relative ages of the other clusters with respect to M68 have been derived by means of the horizontal method and are displayed in Table 1.

Recently, Reid (1997) has used HIPPARCOS parallaxes for nearby metal-poor subdwarfs to determine improved absolute V magnitudes, which we used in order to derive the distance modulus by means of the MS fitting method (see, e.g., Sandquist et al. 1996). We have considered only objects with an error in the parallax determination of less than 12% and a metallicity including an average $[\alpha/{\rm Fe}] = 0.3$ not higher than $Z \approx 0.0006$, such that the colour corrections to be applied to this empirical subdwarf sequence to match the metallicity of M68 are minimized. In order to have stars representative of the un-

Table 1. Halo Globular Cluster data. The columns display respectively: cluster name, global metallicity (including α-enhancement), absolute age with the associated formal error, relative age with respect to the reference cluster, HB type, galactocentric distance (in kpc), estimated level of the observational ZAHB (only for reference clusters). The absolute age is obtained by means of the vertical method for the reference clusters and by adding the relative ages for all other clusters in the same group.

Name	[M/H]	Age	Rel. age	HB type	R_{GC}	V_{zahb}
		$-2.1 \leq$ [M/H] < -1.6				
NGC4590 (M68)	-1.90	12.2±1.0		0.44	10.2	15.72±0.04
NGC6341 (M92)	-2.04	11.8±1.1	-0.4	0.88	9.5	
NGC7099 (M30)	-2.03	12.7±1.1	0.5	0.88	7.3	
NGC7078 (M15)	-1.95	12.2±1.1	0.0	0.72	10.5	
NGC6397	-1.70	12.2±1.1	0.0	0.93	5.9	
NGC2298	-1.65	12.5±1.1	0.3	0.93	17.0	
Arp2	-1.65	10.6±1.1	-1.6	0.86	24.4	
Rup106	-1.65	10.1±1.1	-2.1	-0.82	18.7	
		$-1.6 \leq$ [M/H] < -1.3				
NGC6584	-1.34	11.0±1.1		-0.09	6.6	16.60±0.05
NGC3201	-1.36	10.5±1.2	-0.5	0.08	10.1	14.90±0.05
NGC1904 (M79)	-1.49	11.0±1.2	0.0	0.89	19.0	
NGC5272 (M3)	-1.46	11.0±1.2	0.0	0.08	11.9	
NGC6254 (M10)	-1.40	11.0±1.2	0.0	0.94	4.7	
NGC6752	-1.34	10.5±1.2	-0.5	1.00	5.2	
NGC7492	-1.31	11.0±1.2	0.0	0.90	24.8	
		$-1.3 \leq$ [M/H] < -0.9				
NGC5904 (M5)	-1.20	10.9±0.8		0.37	6.2	15.15±0.05
Pal5	-1.27	9.3±0.9	-1.6	-0.40	17.3	
NGC288	-1.20	9.8±0.9	-1.1	0.95	11.7	
NGC1851	-1.13	8.9±0.9	-2.0	-0.33	17.6	
NGC362	-1.07	9.7±0.9	-1.2	-0.87	9.2	
Pal12	-0.94	7.5±0.9	-4.0	-1.00	17.0	
		$-0.9 \leq$ [M/H] < -0.6				
NGC6171 (M107)	-0.79	11.0±1.1		-0.76	3.6	15.72±0.04
NGC6652	-0.69	8.0±1.2		-1.00	1.6	15.95±0.05
Ter7	-0.80	6.5±1.2	-4.5	-1.00	27.5	
NGC6366	-0.79	13.2±1.2	2.2	-1.00	4.9	

evolved part of the MS, only objects fainter than absolute magnitude 5.8 have been selected. Six stars were found which satisfy all these requirements. Assuming the M68 metallicity given in Tab. 1 with an error of ±0.20 dex, a reddening of 0.07 ± 0.01 as given by Walker (1992b), and the colour corrections given by our isochrones, which we extended for this purpose down to lower masses, we obtain $(m-M)_{V,subdw}$=15.43±0.19. Within the errors this value, obtained by using the subdwarfs with HIPPARCOS parallaxes, agrees with that obtained from the ZAHB.

Gratton et al. (1997) performed a similar study based on high precision trigonometric parallaxes from HIPPARCOS, coupled with accurate high resolution spectroscopic determinations of [Fe/H] and [α/Fe] for a sample of about 100 subdwarfs. The average α-element enhancement that they determine is about 0.3 dex for [Fe/H] < -0.5. With these data they define the absolute location of the empirical MS as a function of [M/H], and determine the distances to 9 GCs by means of the MS fitting method, using a relation for the scaling of the $(B-V)$-colour of the empirical MS with respect to the metallicity that matches the observations and is in good agreement with the one derived from our models. Among their sample of GCs there are two of our template clusters, namely M68 and M5 (see below). For M68 they get $(m-M)_{V,subdw} = 15.37 \pm 0.10$ to be compared with our value of 15.26, which becomes $(m-M)_V = 15.23 \pm 0.06$, if we take into account the slightly higher metallicities used by Gratton et al. (1997). Thus, also this distance modulus derived from HIPPARCOS subdwarfs agrees within the errors with our value.

As an example for the determination of relative ages we show in Fig. 3 the fiducial lines of NGC2298 and M92 registered to that of M68 as described in the previous section; the two dashed lines parallel to the RGB of M68 correspond to an age variation of ±1 Gyr with respect to the age of M68. When neglecting Rup106 and Arp2, this group is remarkably homogeneus in age (an occurrence already discussed by VandenBerg et al. 1990 and Straniero & Chieffi 1991), the maximum age difference with respect to M68 being ≈ 0.5 Gyr.

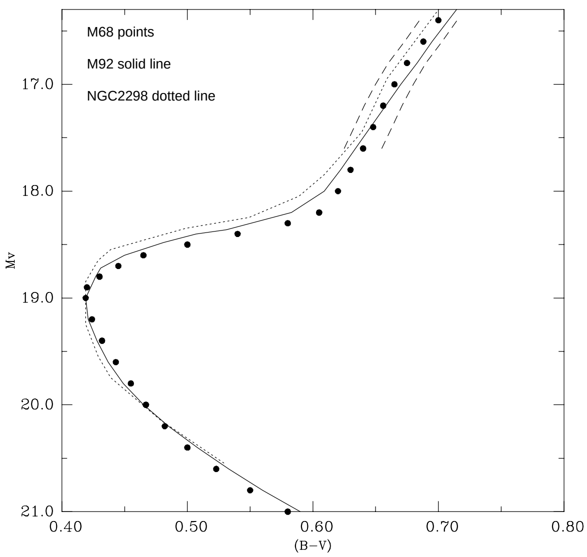

Fig. 3. Comparison of CMD ridge lines registered to that of M68 as explained in the text. The dashed lines on both sides of the M68 RGB indicate an age difference of ±1 Gyr with respect to this cluster

Rup106 and Arp2 have been included in this group following the metallicity determinations by Buonanno et al. (1993, 1995a), which are based on the characteristics of the observed cluster RGBs. The final value for [M/H] has been obtained by adding the contribution of the α-elements as for the other clusters. The main lines of Rup106, Arp2 and M68 are displayed in Fig. 4, shifted as before; Rup106 and Arp2 appear to be younger by $\approx$ 2 Gyr with respect to M68. This age difference is only half as large as that claimed by Buonanno et al. (1993, 1995) with respect to an 'average' metal-poor cluster, obtained by averaging the fiducial lines of M92 (Stetson & Harris 1988), M68 (McClure et al. 1987), NGC6397 (Buonanno et al. 1989), M15 (Fahlman et al. 1985) and M30 (Richer et al. 1988).

In this work we have compared Rup106 and Arp2 with the new M68 photometry by Walker (1994), and the differences in the average $\Delta(B-V)$ values of Rup106 and Arp2 with respect to M68 are, respectively, +0.041 mag and +0.030 mag, almost coincident with the values +0.041 mag and +0.028 mag found by Buonanno et al. (1993, 1995a). The smaller age difference is due to the fact that the relative ages determined with the horizontal method depend on the absolute age of the template cluster for the age range we are dealing with (the same behaviour is found when considering, for example, the Straniero & Chieffi 1991 or the Bergbusch & Vandenberg 1992 isochrones). If an age of 16 Gyr were assumed for M68, we would find that Rup106 is younger than M68 by $\approx$4 Gyr, and that Arp2 is $\approx$1 Gyr older than Rup106, in good agreement with the results found by Buonanno et al (1995a).

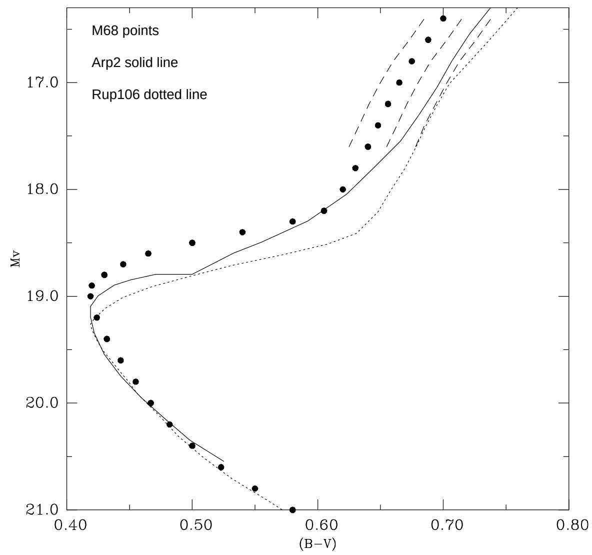

Fig. 4. As Fig 3, but for Rup106 and Arp2; in this case the dashed lines correspond to age differences of +1, -1 and -2 Gyr with respect to M68

For testing in a different way the reliability of the relative ages of Rup106 and Arp2 with respect to M68 as derived from the horizontal method, we have checked if the same age difference is consistent with that obtained from the vertical method (in a very similar way as in Buonanno et al. 1993). As displayed in Fig. 5, we have considered the Rup106 photometry (the Arp2 photometry shows only a very poorly populated blue HB), and we have shifted horizontally and vertically the CMD and ridge line in order to superimpose them on the HB and RGB of M68; note the almost coincident shapes of the RGBs, which indicate a very similar metallicity for these two clusters. The TO luminosities given by the observers are 21.05 mag for Rup106 and 19.05 mag for M68; the vertical shift applied to Rup106 is -2.2 mag, and the horizontal one is -0.17 mag. The difference in the TO luminosities gives the age difference from the vertical method. Shifted in this way, the TO of Rup106 differs by 0.2 mag (Rup106 TO being more luminous) with respect to the M68 TO, and correspondingly Rup106 is $\approx$ 1.7 Gyr younger than M68, in very good agreement with the value derived from the horizontal method.

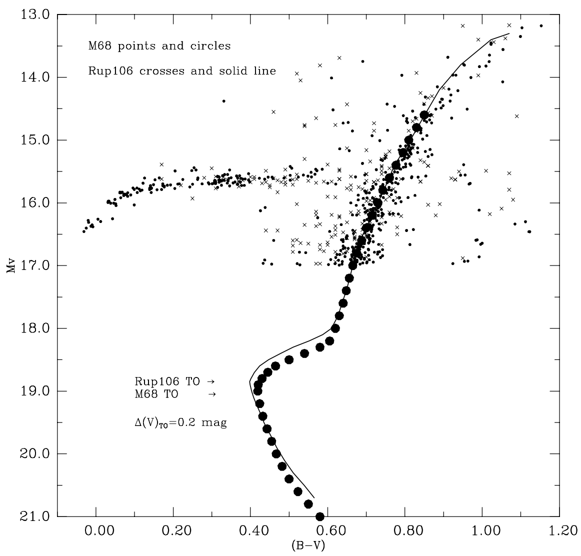

Fig. 5. Rup106 CMD and ridge line shifted in order to superimpose RGB and HB to the M68 ones. The cluster TO luminosities are indicated

3.2. Intermediate metal-poor clusters: $-1.6 \leq$ [M/H] < -1.3

In this metallicity range we have considered the following clusters: NGC6584 (Sarajedini & Forrester 1995), M3 (Ferraro et al. 1996), M79 (Ferraro et al. 1992), NGC6752 (VandenBerg et al. 1990), NGC7492 (Coté et al. 1991), M10 (Hurley et al. 1989) and NGC3201 (Covino & Ortolani 1997).

The reference cluster is NGC6584. From the vertical method, using a metallicity $Z = 0.001$, we derive t=11.0±1.1 Gyr (see Fig. 6; we obtain an apparent distance modulus of $(m-M)_V = 16.01 \pm 0.05$ and a reddening of $E(B-V) = 0.13$, in agreement with previous estimates ranging between 0.07 and 0.15. By applying the horizontal method, we derive age differences not bigger than 0.5 Gyr for all clusters in the sample (see Table 1).

In Fig. 6 (as in Fig. 11) the observational data appear to be quantized; this is due to the fact that the available files with the photometric data provide V and (B-V) values with only two decimal digits. However, the fiducial line and the TO luminosity we use are the ones provided in the cited papers and were derived by the authors using the original data with more than two decimal digits. Moreover, this quantization does not affect the derived observational value of the ZAHB brightness, which is determined with an error of typically ±0.05 mag.

In the case of NGC6584 we have verified that using a metallicity of $Z = 0.0006$, which corresponds to the lower boundary of the error range associated with the metallicity determination ([M/H] of 0.2 dex), the isochrone fit can be improved. The absolute age is changed by only ≈ 0.5 Gyr, and the relative ages determined by means of the horizontal method are affected much less.

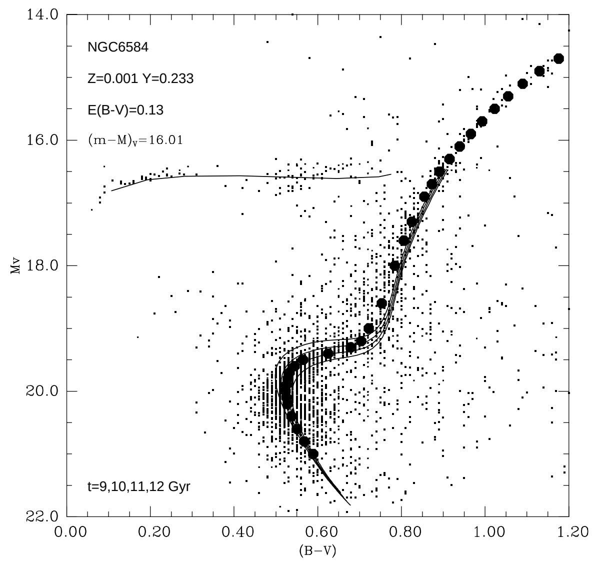

Fig. 6. Isochrones for ages between 9 and 12 Gyr and ZAHB theoretical models compared to the CMD and the ridge line of NGC6584 (Sarajedini & Forrester 1995)

We can check the consistency of the horizontal age determination with the absolute vertical age determination for another cluster with a well populated horizontal part of the HB, that is NGC3201 (Covino & Ortolani 1997). We get an age of 10.0 ± 1.6 Gyr from the vertical method ($(m-M)_V = 14.28 \pm 0.05$, $E(B-V) = 0.25$) adopting $Z = 0.001$ (see Fig. 7); this value is in very good agreement with the age obtained by means of the horizontal method relative to NGC6584 (see Table 1 and Fig. 8).

We have also calculated the age of Rup106 in a third way by assigning it to the intermediate metal-poor group and by deriving its relative age with respect to NGC6584. These two clusters differ by ≈ 0.3 dex in [M/H], and in principle – following the criteria adopted in this work – could belong to the same metallicity group. Rup106 is measured to be 1.3 Gyr younger than NGC6584; thus the derived absolute age in this case is 9.7±1.2 Gyr, consistent with the value derived in the preceding subsection (see Tab. 1).

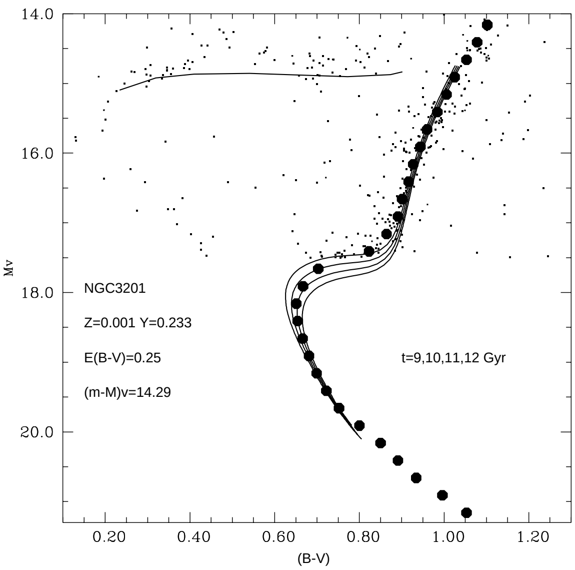

Fig. 7. Isochrones for ages between 9 and 12 Gyr and ZAHB theoretical models compared to the CMD and ridge line of NGC3201 (Covino & Ortolani 1997). For sake of clarity, only the ridge line is displayed for the cluster MS

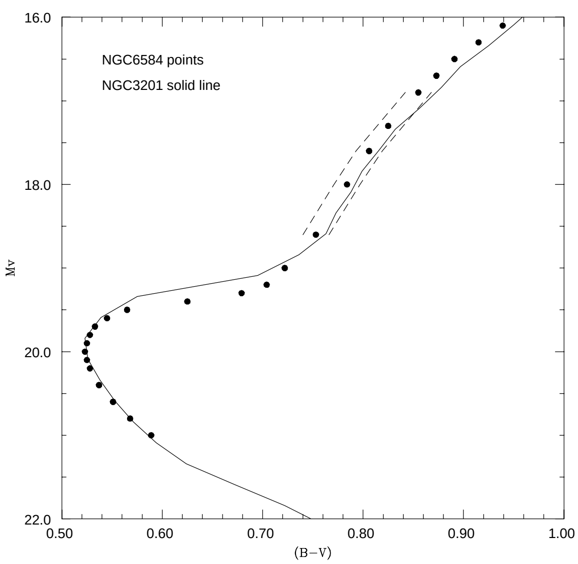

Fig. 8. The CMD ridge line of NGC3201 registered to that of NGC6584 as explained in the text. The dashed lines on both sides of the NGC6584 RGB indicate an age difference of +1 and -1 Gyr with respect to NGC6584

3.3. *Intermediate metal-rich clusters:* $-1.3 \leq$ [M/H] < -0.9

This group includes M5 (Sandquist et al. 1996), NGC1851 (Walker 1992b), NGC288 (Bolte 1992), NGC362 (VandenBerg et al. 1990), Pal12 (Stetson et al. 1989) and Pal5 (Smith et al. 1986).

The reference cluster is M5. By applying the vertical method to the recent photometric data by Sandquist et al. (1996), and using Z=0.0015 we get an age of 10.9±0.8 Gyr (see Fig. 9) and $E(B-V) = 0.06$, $(m-M)_V = 14.55 \pm 0.05$. If we compute the real distance modulus, by adopting $A_V = 3.3E(B-V)$, we get $(m-M)_0 = 14.35 \pm 0.05$, a value that agrees well with the value of 14.37 ± 0.18 found by Storm et al. (1994) from the Baade-Wesselink method for two cluster RR Lyrae stars. Our $(m-M)_V$ is also confirmed by the recent result of Gratton et al. (1997), $(m-M)_{V,subdw} = 14.58 \pm 0.04$, which is based on HIPPARCOS subdwarf parallaxes (see Sect. 3.1), even if we take into account the slightly higher metallicity for M5 used by Gratton et al. (1997). In this case, our distance modulus becomes $(m-M)_V = 14.50 \pm 0.07$.

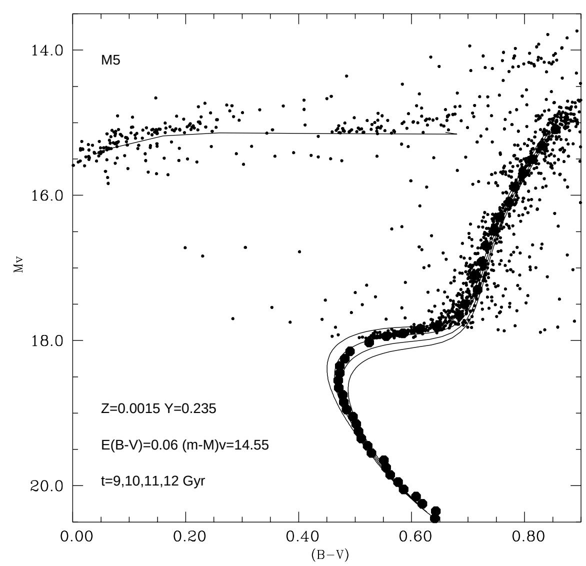

Fig. 9. Isochrones for ages between 9 and 12 Gyr and ZAHB theoretical models compared to the CMD and ridge line of M5 (Sandquist et al. 1996). Only the ridge line is displayed for the cluster MS, and along the RGB, at luminosities lower than the HB, only a subsample of stars is shown

The relative ages with respect to M5 are displayed in Table 1. All the other clusters are found to be significantly younger, the youngest one being Pal12. In par-

ticular, when taking into account the recent photometric study by Bolte (1992) of NGC288, we find that NGC288 and NGC362 are practically coeval (see Fig. 10). This confirms the qualitative result by Stetson et al. (1996), who found using essentially the vertical method that NGC1851, NGC362 and NGC288 should have the same age, thus giving very strong evidence against age as the second parameter. Our result is in agreement with their investigation; by using the horizontal method, the three clusters are found to be coeval within less than 1 Gyr (Fig. 10)).

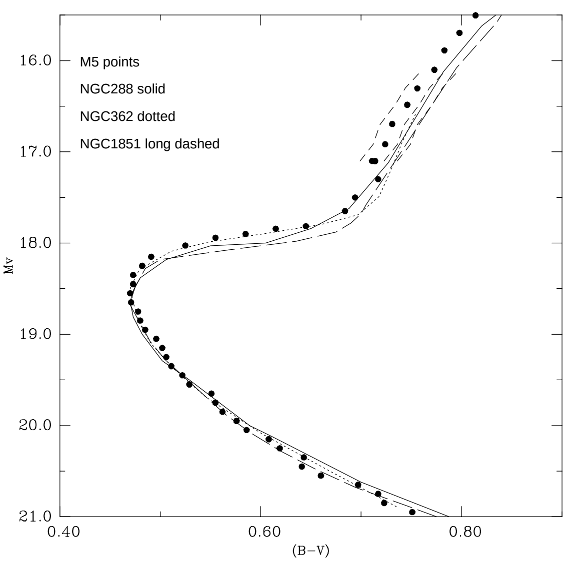

Fig. 10. Comparison of CMD ridge lines. The dashed lines on both sides of the M5 RGB indicate an age difference of +1, -1 and -2 Gyr with respect to the reference cluster M5

3.4. Metal-rich clusters: $-0.9 \leq [\mathrm{M/H}] < -0.6$

M107 (Ferraro et al. 1991), NGC6652 (Ortolani et al. 1994), NGC6366 (Alonso et al. 1997) and Ter7 (Buonanno et al. 1995b) are the four clusters considered in this group. The reference cluster is NGC6171 (=M107). By employing isochrones for $Z = 0.004$ we get from the vertical method an age of 11.0 ± 1.1 Gyr, together with $E(B-V) = 0.38$ and $(m-M)_V = 15.02 \pm 0.04$ (see Fig. 11). The reddening we derive agrees with previous estimates, ranging between 0.30 and 0.48.

By applying the horizontal method with respect to M107 (see Fig. 12), we find a large age spread within this group: NGC6366 is ≈ 2 Gyr older than M107, while Ter7 is ≈ 4.5 Gyr younger than M107. This is the largest age spread among all the clusters considered in this

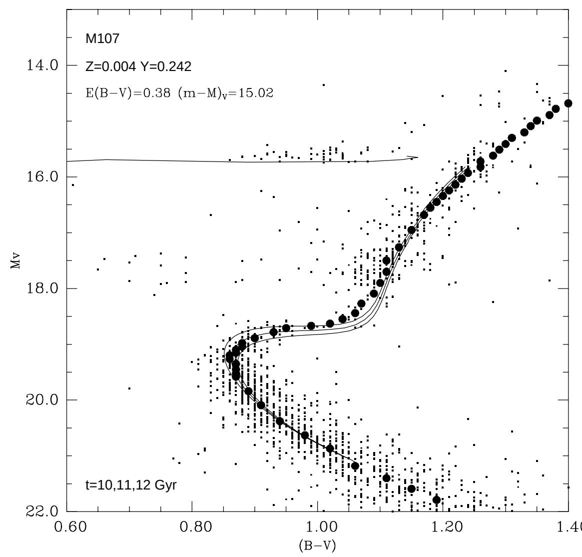

Fig. 11. Isochrones for ages between 10 and 12 Gyr and ZAHB theoretical models compared to the CMD and ridge line of M107 (Ferraro et al. 1991)

study. However some caution is required when considering NGC6366, since this cluster (see Harris 1993 and Alonso et al. 1997) is affected by differential reddening; the determination of its relative age with respect to NGC6171 could therefore be less accurate even if the cluster appears undoubtedly to be an "old" halo GC (see also the discussion in Alonso et al. 1997).

The cluster ridge line for NGC6652 (not provided in the paper by Ortolani et al. 1994) has been derived by determining the median of the colour distribution within brightness bins. The resulting TO luminosity is in very good agreement with the value V_{TO}=19.20±0.15 given by Ortolani et al. (1994). Since the cluster RGB shows a large dispersion in colour and the ridge line for this CMD region is not well defined, we have considered the ridge line only up to the subgiant branch. Together with a very well defined and populated red HB, this is sufficient for directly estimating the absolute cluster age (as given in Table 1) by means of the vertical method. By using isochrones for $Z = 0.004$ we get an age of 8.0±1.2 Gyr, $E(B-V) = 0.23$, $(m-M)_V = 15.23$ (see Fig. 13).

The consistency between the NGC6652 absolute age and its relative age with respect to M107 derived by means of the horizontal method can be checked qualitatively by registering the M107 ridge line to that of NGC6652, as shown in Fig. 14. Since the RGB of NGC6652 shows a large dispersion in colour, it is not possible to derive a reliable independent estimate of its relative age with respect to M107, but we can verify the consistency of the relative

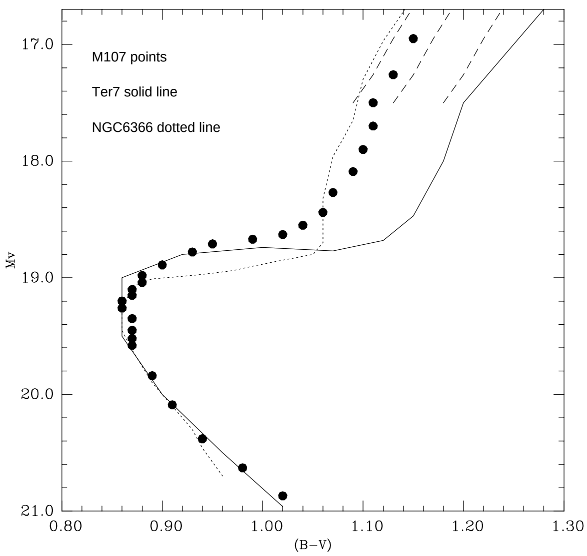

Fig. 12. Comparison of CMD ridge lines. The dashed lines on both sides of the M107 RGB indicate an age difference of +2, -2 and -4 Gyr with respect to this cluster

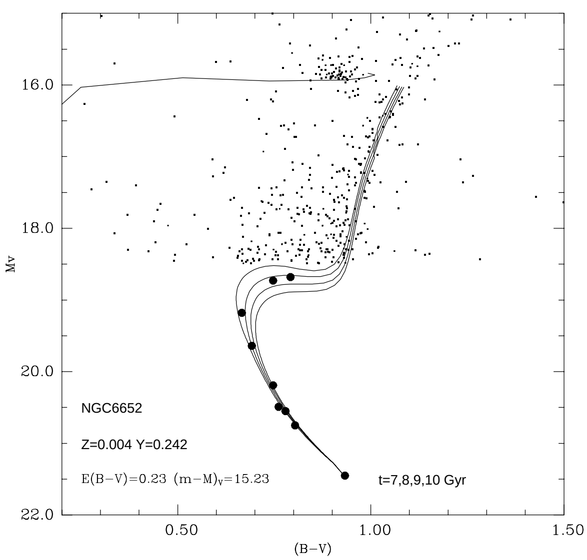

Fig. 13. Isochrones for ages between 7 and 10 Gyr and ZAHB theoretical models compared to the CMD and ridge line of NGC6652 (Ortolani et al. 1994). Only the ridge line is displayed for the cluster MS

RGB positions with the absolute ages. If we consider the magnitude range $M_V \approx$ 16-17, where the NGC6652 RGB appears to be better defined, the M107 fiducial line lies at the left boundary of the NGC6652 RGB, while the line corresponding to an age difference of -4 Gyr with respect to M107 lies to the right of the RGB. Recalling that the absolute ages of M107 and NGC6652 as obtained by means of the vertical method are, respectively, 11.0 and 8.0 Gyr, the relative positions of the RGBs are in qualitative agreement with the difference in absolute ages.

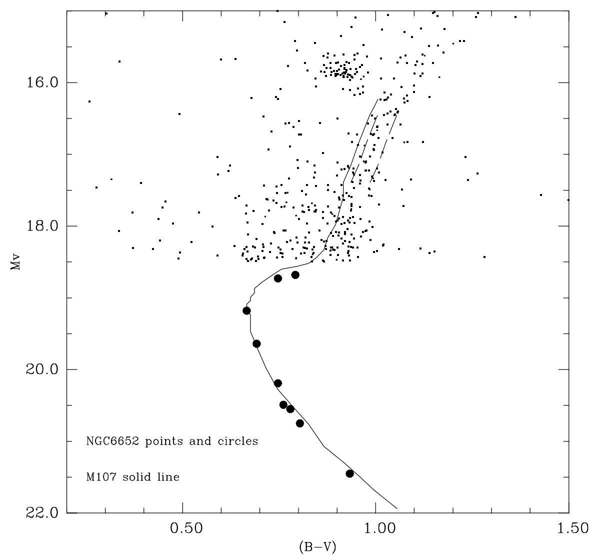

Fig. 14. Relative age of NGC6652 with respect to M107 derived from the horizontal method. The dashed lines on the right side of the M107 RGB indicate an age difference of -2 and -4 Gyr with respect to this cluster

3.5. Comparison with previous results

The GC ages displayed in Table 1 can be directly compared with the results from the work by Richer et al. (1996). Their approach has already been discussed in Sect. 1. They also arranged the clusters into four groups, according to the cluster [Fe/H]-content. The metallicity range of each group is very similar to our choice, as are the metallicities adopted for each cluster. Only in the case of Rup106 and Arp2 they are substantially higher. As for the absolute ages, we find that our values are systematically lower by $\approx$ 4 Gyr, due basically to the more up-to-date stellar models we used (see Paper I).

The relative ages among the metal-poor GCs in common with Richer et al. (1996) are in agreement with their results within the formal errors associated with the de-

termination of the relative ages ($\approx$ 0.5 Gyr for both this paper and Richer et al. 1996).

When considering the second group (intermediate metal-poor clusters), we have in common with Richer et al. (1996) M3, NGC6752, NGC1904 and NGC7492, which are coeval within 0.5 Gyr. Richer et al. (1996) find the same result for the first 4 cluster, while they obtain an age 1.7 Gyr higher for NGC7492. This is surprising, since we are using the same source of photometric data for example for NGC6752 and NGC7492. The reason for this difference could be due to a point on the ridge line of NGC7492 that is clearly discrepant. It is about 2.5 mag brighter than the point on the main sequence used for registering all clusters to the reference one. If only this point is considered for determining the relative age, one indeed finds that NGC7492 is around 1.7 Gyr older than NGC6752.

In the intermediate metal-poor group Richer et al. (1996) also include Arp2 and Rup106. They find that Rup106 is younger by 1 Gyr with respect to Arp2, and by 4 Gyr with respect for example to NGC6752. We also determined the relative age of Rup106 with respect to clusters of the second group (see Sect. 3.4), and the result is that it is younger by only $\approx$ 1.3 Gyr. As previously discussed, this result is due to the dependence of the relative ages obtained by the horizontal method on the absolute age of the reference cluster, for ages lower than a certain value depending on the assumed metallicity.

The intermediate metal-rich clusters in common with Richer et al. (1996) are M5, NGC288, NGC362, NGC1851 and Pal12. The substantial difference with their work is that we find NGC1851, NGC288 and NGC362 to be coeval within 1 Gyr (in agreement with the result by Stetson et al. 1996 obtained by the vertical method). This seems to be due to the use of the new Bolte (1992) photometry for NGC288. Had we used the NGC288 ridge line from Buonanno et al. (1989), we would have obtained an age difference by $\approx$2 Gyr with respect to NGC362 (NGC288 being older), in agreement with the results by Richer et al. (1996). Another difference is that we have adopted the very recent M5 photometry by Sandquist et al. (1996), which also displays a well-populated HB, and we find that M5 is older than NGC362 and NGC1851, while Richer et al. find these three clusters to be coeval; this difference again is due to the different data used. If we use the old data for M5 by Richer & Fahlman (1987, as in Richer et al. 1996), the results again agree with Richer et al. (1996).

Among the metal-rich clusters there is only Ter7 in common with the work by Richer et al. (1996). They consider 3 other clusters belonging to the disk GC system, for which there are indications that the original helium content could be substantially higher than $Y = 0.23$ (see Alonso et al. 1997 and references therein).

4. Discussion

The results displayed in Table 1 can be used for checking for the existence of an age spread and an age-metallicity relation for halo clusters, as well as for testing the hypothesis that age is the so-called "second parameter", responsible for the HB morphology of galactic GCs.

Recent work by Chaboyer et al. (1996) reaches the conclusion that age is the second parameter, but the analyses by Richer et al. (1996) and Stetson et al. (1996) do not confirm this. Checking Table 1, it is evident that the cluster pairs Rup106–Arp2 and NGC288–NGC362 have almost the same metallicity and ages, but completely different HB morphologies. We support therefore the conclusion that HB morphology must, at least in part, be due to causes other than only metallicity and age.

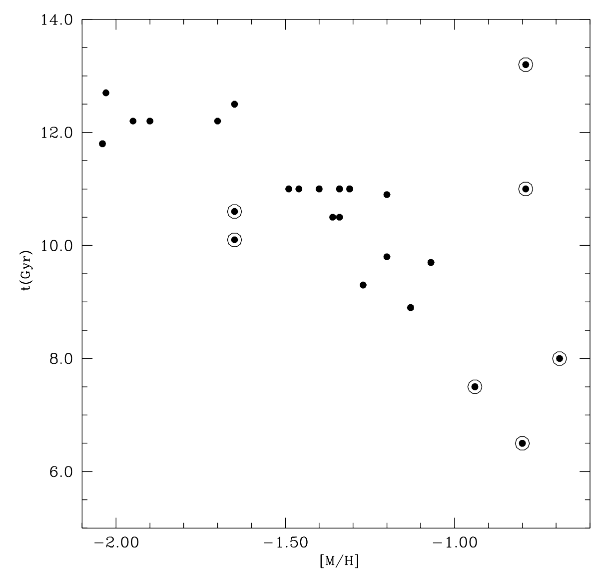

Fig. 15. Age (in Gyr) of the 25 clusters in our GCs sample as a function of their [M/H]. The clusters with the circled dots (Rup106, Arp2, Ter7, Pal12, NGC6366, M107, NGC6652) are those excluded from the analysis is some cases (see text). The error on the individual ages (of order $\pm$1 Gyr) can be found in Table 1, while the error on [M/H] is typically of the order of 0.20 dex

As for the cluster age distribution, we find that if we take into account all 25 GCs considered in our investigation (see Table 1, Fig. 15, Fig. 16), we obtain an average age of $\langle t \rangle$ = 10.6 Gyr, with a standard deviation σ=1.7 Gyr. However, as discussed in the previous section, the relative age of NGC6366 with respect to M107 is uncertain, due to differential reddening, and therefore we will

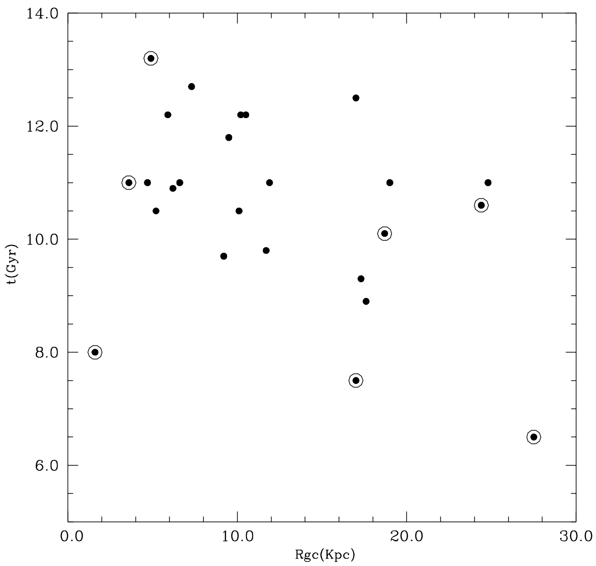

Fig. 16. As in the previous figure, but in this case the age is displayed as a function of the cluster galactocentric distance (in kpc)

not consider NGC6366 in the following analysis. Without NGC6366 (24 clusters), $\langle \mathrm{t} \rangle$ = 10.5 Gyr and σ=1.6 Gyr, very close to the results for the complete sample. For the first three metallicity groups the average ages and the dispersions are, in the order of increasing metallicity, $\langle \mathrm{t} \rangle$ = 11.8, 10.9, 9.4 Gyr and σ = 0.9, 0.2, 1.1 Gyr. In the most metal-rich group we have only three clusters, which have $\langle \mathrm{t} \rangle$=8.5 Gyr. The rather large variance for the low-metallicity group results from the two clusters Arp2 and Rup106. If we omit these clusters (see below), we obtain $\langle \mathrm{t} \rangle$ = 12.3 and σ = 0.3.

To quantify how much of the age range among the clusters could be due to errors and whether a real intrinsic age range exists, we have performed the same statistical test used by Chaboyer et al. (1996). We have calculated an "expected" distribution for the assumption of no intrinsic age range by randomly generating 10000 ages using a Gaussian distribution. The mean of the distribution was given by the mean age of the clusters (10.5 Gyr) , and the σ by the error on the individual age determinations. This is repeated for all clusters considered, so that the final distribution contains 240000 points. The F-test (Press et al. 1992) was then applied in order to determine if this "expected" distribution has the same variance as the age distribution obtained in our analysis. As in Chaboyer et al. (1996) we state that an age range exists if the probability that the two distributions have the same variance is smaller than 5%.

The F-test rejects the possibility that the clusters are coeval with a confidence level higher than 99.8%. The size of the true age range (σ_{range}) can be estimated according to $\sigma_{range} = (\sigma_{obs}^2 - \sigma_{exp}^2)^{0.5}$, where σ_{obs} is the sigma of the actual data, and σ_{exp} is the sigma of the expected distribution (Chaboyer et al. 1996); we obtain σ_{range}=1.2 Gyr.

As for an age-metallicity relation, a formal linear fit to the data yields

$$t = (-3.27 \pm 0.53)[\mathrm{M/H}] + (5.94 \pm 0.77). \tag{3}$$

The linear Pearson correlation coefficient is -0.80, implying that the confidence level for a linear correlation between age and [M/H] is not high. The correlation coefficient for the relation between age and R_{GC} is even lower (-0.34). A visual inspection of Fig. 16 confirms that there is only an indication that the youngest clusters, with the exception of NGC6652, seem to be located in the outer Halo.

To summarize, when considering all the clusters in our sample (except NGC6366), we find an age spread among the GCs (σ_{range}=1.2 Gyr), but no statistically compelling evidence for either an age-metallicity or an age-R_{GC} relation. There is however an indication that the more metal-poor clusters are on average older then the clusters of higher metallicities, and that the age spread within each metallicity bin tends to be higher for increasing metallicities. Our analysis based on new stellar models therefore confirms the results of Richer et al. (1996) in this respect.

Recently, Lin & Richer (1992) and Buonanno et al. (1994) have suggested that Pal12, Rup106, Arp2 and Ter7 (which appear to be younger than other clusters of approximately the same metallicity) could have been captured by the Milky Way from a companion galaxy, and therefore represent later infall events. In this case they could not be indicative of the halo formation phase. This argument is based mainly on the fact that these four clusters appear to lie along a single great circle passing through the northern tip of the Magellanic Stream, thus suggesting a common orbit that could be the result of an accretion event from a companion galaxy. Although it is clear that proper motion studies are necessary for a definitive answer, the argument is reinforced by the fact that Ter7 and Arp2 lie very close to the Sagittarius Dwarf Galaxy (but see also the discussion in Chaboyer et al. 1996), which is currently being tidally disrupted and absorbed by the Milky Way.

If this is the case, the previous statistical analysis should be performed excluding these 4 objects from our halo GCs sample. Furthermore, from Fig. 15 it is evident that there are only two clusters of the metal-rich group left – M107 and NGC6652 (at respectively 11 and 8 Gyr). In the following we will give results in brackets for the case when M107 and NGC6652 are neither taken into account, and therefore the highest metallicity clusters are disregarded completely. The average age of the remaining 20 (18) clusters is then $\langle \mathrm{t} \rangle$ = 10.9 (11.0) Gyr (σ=1.2

(1.1) Gyr), which is slightly older, but has a much narrower distribution than the complete sample. The correlation coefficient between age and metallicity is almost -0.82 (-0.86), which is the same as for the 24 clusters. The F-test reveals that the "coeval" hypothesis can be rejected with a lower confidence level of ≈70% (25%); the derived formal σ_{range} is equal to 0.5 (0.2) Gyr, less than half of σ_{range} for the complete sample. We therefore conclude that, once Pal12, Rup106, Arp2 and Ter7 are excluded, the genuine halo clusters formed within ≈ 1.5 Gyr of each other. Our smallest sample is therefore coeval and the one including M107 and NGC6652 cannot be excluded to be so as well. The formal linear regression to this sample gives $t = (-2.71 \pm 0.45)[\mathrm{M/H}] + (7.03 \pm 0.66)$.

5. Summary

Our results can be summarized as follows:

1. We have determined the ages of a sample of 25 halo clusters by use of stellar models which take into account all recent improvements in stellar input physics data.
2. The method for obtaining ages is a combination of the $\Delta(V)$-method for a few "reference" clusters and the $\Delta(B-V)$-method for other clusters of a similar metallicity. The clusters are split into four groups according to simila metallicity.
3. Our results, summarized in Table 1, confirm that GCs are $\approx 12\pm1$ Gyr old or younger, as we already claimed in Paper I for a subset of three metal-poor clusters. The lower ages as compared to previous investigations are due to our new stellar physics input and our purely theoretical approach for the HB luminosities.
4. Since age differences depend on absolute age, we obtain smaller age differences for a given $\Delta(B-V)$. Therefore our sample becomes more homogeneous even if we use the same original data as in previous papers. This applies, e.g., for Rup106 and Arp2 with respect to M68.
5. Several cross checks (e.g. for Rup106) result in consistent ages.
6. NGC6366 is the oldest cluster of our sample with 13.2 ± 1.2 Gyr, but the photometry for this cluster might be affected by differential reddening, so we excluded it from the analysis in Sect. 4. The next oldest cluster is M30 with 12.7 ± 1.1.
7. We confirm earlier results that the metal-poor clusters form a very coeval group and that the more metal-rich groups show a larger age spread.
8. For the whole sample, which has not been selected on any specific grounds except that the photometric quality should allow the application of our age determination methods, we obtain a mean age of 10.6 ± 1.7 Gyr (1σ-error) and reject the assumption that all clusters are coeval. A linear correlation between metallicity and age is not confirmed.
9. For samples with all "peculiar" and metal-rich clusters excluded, the mean age becomes better defined (11.0 ± 1.1 Gyr). The age range of a large sample of clusters with the same average age and individual errors as ours would be only 0.2 Gyr (1σ range). The clusters in this sample are coeval. This is still true, if we include M107 and NGC6652, although the probability for this hypothesis is lower. Whether or not the assumption of a common age can be rejected safely, depends critically on the inclusion of individual clusters. Clearly, the sample size is too small for any reliable conclusions.
10. There is no evidence for any correlation between age and galactocentric distance.
11. Known counter-examples against the hypothesis that age is the second parameter affecting HB morphology are confirmed. NGC288 and NGC362 have the same age. This result does not agree with Richer et al. (1996), and is due to new photometric data of NGC288, but it is in agreement with the results by Stetson et al. (1996).
12. Other differences with respect to Richer et al. (1996) can be explained in terms of our new models, lower absolute ages, or different original data.

We confirm and substantiate the results of Richer et al. (1996) in large parts, although differences for individual clusters exist, and we determine significantly lower ages for all clusters. According to both investigations the more metal-poor GCs all formed within 1 Gyr and throughout the whole halo. The more metal-rich systems possibly formed another Gyr later and over a somewhat longer timescale. The cluster population is contaminated by a few clusters not fitting into this simple picture. Consistent and high-quality photometric data for a large sample of clusters is needed to confirm our results.

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